

Two-component radiation model of the sonoluminescing bubble

David Tsiklauri

Physics Department, University of Cape Town, Rondebosch 7700, South Africa and Department of Theoretical Astrophysics, Abastumani Astrophysical Observatory, 2^A A. Kazbegi ave., Tbilisi 380060, Republic of Georgia. Internet: tsiklauri@phisci.uct.ac.za

(February 1, 2008)

Based on the experimental data from Weninger, Putterman & Barber, Phys. Rev. (E), **54**, R2205 (1996), we offer an alternative interpretation of their experimental results. A model of sonoluminescing bubble which proposes that the electromagnetic radiation originates from two sources: the isotropic black body or bramsstrahlung emitting core and dipole radiation-emitting shell of accelerated electrons driven by the liquid-bubble interface is outlined.

78.60.Mq, 47.70.Mc, 43.35.+d

Theoretical explanation of the sonoluminescence has been a long standing puzzle since 1934 when it was observed for the first time [1]. The most viable theoretical models of the phenomenon are based on so called shock wave model [2] which is capable to explain certain characteristic features of the effect. However, this model is constrained by the assumption of the spherical symmetry of the bubble during all stages of its collapse.

However, recent pioneering experimental studies [3] convincingly showed existence of an emission component with dipole angular distribution of intensity which strongly suggests presence of some kind of non-spherical dynamics of the bubble.

Angular dependence in the intensity of sonoluminescence can be described by the following correlation [3]

$$\Delta Q_{AB}(\theta_{AB}) = \frac{1}{\bar{Q}_A \bar{Q}_B} \left\langle (Q_A(i) - \bar{Q}_A) (Q_B(i) - \bar{Q}_B) \right\rangle_i, \quad (1)$$

where θ_{AB} is the angle formed by the photomultiplier tubes A and B and the bubble which is positioned at the vertex. $Q_A(i)$ is the total charge recorded in the detector A on the i -th flash, \bar{Q}_A is the running average of $Q_A(i)$ and $\langle \rangle_i$ denotes an average over i . Major experimental results obtained by the authors of Ref.[3] are as follows:

- (i) detection of two light emission components with isotropic and dipole angular distribution through measurement of $\Delta Q_{AB}(\theta_{AB})$.
- (ii) Finding of qualitatively different physical states of the sonoluminescing bubble in which the two emission components have different share in total light intensity.
- (iii) measurement of intensity fluctuations in the different physical states of sonoluminescing bubble.
- (iv) measurement of the correlation ΔQ_{AB} given by Eq.(1) as a function of time delay Δt between acquisitions in detectors A and B .

Authors of Ref.[3] interpreted their experimental results (presence of the dipole emission component) as due to the refraction of light by the non-spherical bubble wall i.e. liquid-bubble interface. Their major argument was that red light ($\lambda > 500$ nm) showed no angular correlation. Whereas, blue light ($260 \text{ nm} < \lambda < 380 \text{ nm}$) was significantly correlated. This experimental fact was interpreted [3] as dominance of diffraction over refraction in the case of long wavelength (since the radius of bubble is about the same size as red light wavelength) and vice versa in the case of short wavelength (blue light).

Below we show that these novel experimental facts can be explained in an alternative way and outline fundamentals of the two component model.

Explanation of presence of the dipole component in terms of the light refraction from the non-spherical liquid-bubble interface [3] implies the primary isotropic core emission comes from a point source which is more likely to be the either black body radiation coming from the contents of the bubble which was heated up by the implosion [4] or bremsstrahlung emitted from the air after it has been ionized by shock compression [2]. Further, light from this point source is refracted from the non-spherical liquid-bubble interface which results in a dipole angular distribution of the detected light [3]. However, it is reasonable to assume that the angularly correlated component primarily has a dipole origin itself. Preliminary numerical simulations showed that liquid-bubble interface achieves substantial accelerations at the final stages of the collapse. The measure of the latter physical quantity could be $\ddot{R}(t)$ (second derivative of the radius with respect to time) calculated from the Rayleigh-Plesset equation which even in *adiabatic* calculation acquires values $\sim 10^{16} \text{ m/sec}^2$. Similar result yields more rough estimate: $a \sim \Delta v / \Delta t \sim 2v / \Delta t$, where v is the maximal velocity acquired during the collapse ($\sim 5 \text{ km/sec}$) and Δt is the time-scale of the radius turnaround ($\sim \text{psec}$). The free electrons which come from ionization of the air will be easily dragged by the liquid-bubble interface since they have small inertia. One could safely assume that typical accelerations of the free electrons dragged by the

liquid-bubble interface will be order of the $\ddot{R}(t)$. It is well known that accelerated, charged particles moving with non-relativistic velocities (which is apparently the case for particles within the sonoluminescing bubble) emit dipole radiation. However, a *spherical* shell of electrons driven by liquid-bubble interface will not emit dipole radiation since the dipole moment of such configuration is zero (unless the electrons are non-uniformly distributed on the interface, which is quite improbable). Previous experimental studies (involving light scattering techniques along with relevant Mie-scattering algorithms) suggest that the bubble remains spherically symmetric until the final stages of the collapse and only then (presumably on the psec time-scale) it becomes distorted by "shape" instabilities [4]. Therefore, at this very instance of time, dipole moment of the system suddenly becomes non-zero. Thus, allowing dipole radiation to take place.

It is important to note that the two component model in which dipole component originates from the dipole emission of shell of electrons dragged by liquid-bubble interface is consistent with the experimental fact [3] that the red light has no angular correlation whereas blue light shows significant angular correlation. It is known that the spectral resolution of the intensity of dipole radiation is given by [5]

$$dE_\omega = \frac{4\omega^4}{3c^3} |\mathbf{d}_\omega|^2 \frac{d\omega}{2\pi} \propto \omega^4. \quad (2)$$

Therefore, since the intensity of the dipole radiation strongly depends on frequency (via Eq.(2)) for low frequencies (red light) intensity of dipole radiation is overwhelmed by the isotropic core (black body or bremsstrahlung) emission, whereas in the case of high frequencies (blue light) dipole radiation is more pronounced.

As we mentioned above yet another significant experimental result of Ref.[3] is the measurement of the angle dependent correlation ΔQ_{AB} , (see Ref.[3] for details) as a function of a time delay Δt between acquisitions in photomultiplier tubes *A* and *B*. This data is important because it provides a clue to determine a source of dipole component. In particular, it has been shown [3] that angle dependent correlation $\Delta Q_{AB}(\Delta t)$ reveals a long time delay which indicates that dipole component is due to the peculiarities of hydrodynamic motion. After excluding various possibilities authors of Ref.[3] concluded that the most viable mechanism is refraction of light by *non-spherical* liquid-bubble interface. Therefore, non-sphericity of the bubble plays a key role in their scenario. However, this argument would also perfectly fit our alternative interpretation of the experimental data, because this is the non-sphericity of the bubble which makes the dipole moment of the shell of electrons driven by the liquid-bubble interface non-zero. Thus allowing the system to emit dipole radiation.

It is also important to address issue of the intensity fluctuations. In ref.[3] it was established that sonoluminescent states where dipole component dominates isotropic component exhibit very large fluctuations in emission intensity. Sonoluminescing states with fraction of dipole component six parts per thousand peak to peak are characterized by intensity fluctuations that are over a factor of 10 greater than states with dipole components of about one part per thousand or less. clue to the explanation of this effect could lay in non-sphericity of the bubble at instance of light emission. Sonoluminescing state with high fraction of dipole component is achieved when there are large deviations from spherical shape of the bubble. Because of this process is chaotic (since it draws its origin from some kind of hydrodynamic instability) and the position of the photomultiplier tube is fixed this results in large fluctuations of intensity. This explanation is equally valid for the refraction model [3] and our two component model, since in both of them cause of dipole emission ultimately is non-sphericity of the bubble.

While mentioning isotropic core emission above, we referred to the black body and bremsstrahlung radiation in an equal manner. However, as we shall see below, thanks to the discovery of the two different sonoluminescing states [3] with no (small) and dominant dipole components, further experimental measurements of the sonoluminescing flash duration could discriminate between black body and bremsstrahlung emission mechanisms as well as between the refraction model [3] and our two component model. As it was emphasized in ref.[4] black body radiation model predicts that the duration of the sonoluminescence light flash should be order of tens of nsec because the temperature of the contents of the bubble is order of 2000K and larger for a time span over 20 nsec. On the other hand, detailed numerical simulations of the shock wave model based on the bremsstrahlung emission assumption confirms tens of psec duration flash [2]. The refraction model [3] which explains presence of dipole component in certain sonoluminescing states apparently will never predict change in the duration of the light flash, since the light is simply refracted from non-spherical liquid-bubble interface. Whereas, in our two component model this is possible because dipole component has different origin — dipole radiation of the accelerated electrons driven by the liquid-bubble interface. Sonoluminescing state in which dipole component is dominant and the core black body emission is assumed deserves particular attention, because in this case our two component model predicts different light flash duration. Dominance of the dipole component in our model means that the core isotropic component (black body radiation) has very low intensity and all detected light comes from the dipole radiation of shell of electrons driven by the liquid-bubble interface. As we mentioned above, dipole emission of such configuration is possible when the bubble loses spherical shape (when the dipole moment suddenly becomes nonzero) which happens at the very final stages of the collapse,

presumably on the psec timescale. Apparently, in this case light refraction model [3] would still predict tens of nsec duration flash since the primary (and the only) emission source is the isotropic black body radiation and of course refraction cannot change the duration of the light flash itself. Authors of Ref. [3] established that the both states (with no (small) and dominant dipole components) exhibit the same flash to flash synchronicity. However, they have not presented measurements for duration of the light flash in both cases. This is important, because under assumption of black body core emission it would allow to discriminate between refraction model and our model. In the case of sonoluminescing state with no (small) dipole component both models would predict the same duration of the light flash which would be order of tens of nsec, since in both cases emission comes from isotropic black body source which has relatively large time scale [4]. Whereas, in the case of sonoluminescing state with dominant dipole component our model would predict short (tens of psec) light flashes and refraction model would still predict long (tens on nsec) flashes. On the other hand assuming that isotropic core emission is of bremsstrahlung type both the refraction [3] and two component model predict the same flash durations tens of psec. We ought to remark that in the literature duration of light flash is claimed to be tens of psec. To the best knowledge of the author, source reference for this information is Ref. [6]. However, awareness of existence of the dipole component emerged from later experimental studies presented in Ref. [3]. Therefore, *a priori* it is unclear whether measured duration of the flash tens of psec [6] was for the state with dominant dipole component or with small one. To clarify this point further experimental studies are necessary.

Finally, we conclude with estimate of the peak power of the sonoluminescence radiation based on the assumption that the all light comes from dipole radiation of shell of electrons dragged by the liquid-bubble interface (dominant dipole state). Typical value of the peak power is order of tens of mW [2]. We know that the total power of dipole radiation of system of accelerated electrons emitted in every direction is [5]

$$I = \frac{2}{3c^3} \ddot{\mathbf{d}}^2, \quad (3)$$

where $\ddot{\mathbf{d}} \equiv \sum e \ddot{\mathbf{r}}$ denotes the second derivative of the total dipole moment with respect to time (\mathbf{r} stands for a radius vector of a particular electron). Apparently, it is impossible to estimate I unless angular distribution and the acceleration of every electron on the non-spherical shell is known. However, assuming that we have system of N electrons moving with plausible acceleration value $a \sim 10^{16} \text{m/sec}^2$ in the same direction (Here we mention that there are models which propose formation of a jet at the final stages of the collapse (see further Refs. [13-14] in Ref.[3])) and putting $\sim 10^{26}$ for the N we end up with reasonable value for the peak power.

As it was argued above, present experimental data allows alternative interpretation. Therefore it is important to perform new experimental measurements of the light flash duration in the two sonoluminescing states with dominant and no (small) dipole components in order to discriminate between the refraction model [3] and our two component model as well as between black body and bremsstrahlung emission mechanisms. Table 1, where we present anticipated durations of the sonoluminescing flash by the refraction [3] and our two component models under the assumption of the black body and bremsstrahlung core emission mechanisms summarizes specific predictions of the models.

-
- [1] H. Frenzel and H. Schultes. Z. Phys. Chem. **27B**, 421 (1934).
 - [2] C.C. Wu and P.H. Roberts, Phys. Rev. Lett. **70**, 3424 (1993).
 - [3] K. Weninger, S.J. Putterman and B.P. Barber, Phys. Rev. (E), **54**, R2205 (1996).
 - [4] L.A. Crum, Physics Today **47** No. 9, 22 (1994).
 - [5] L.D. Landau and E.M. Lifshitz, *The Classical Theory of Fields* (Pergamon Press, New York, 1975).
 - [6] B.P. Barber, R. Hiller, K. Arisaka, H. Fetterman, S.J. Putterman, J. Acoust. Soc. Am. **91**, 3061 (1992).

Table 1. predicted durations of the sonoluminescing flash by the refraction and two component models under the assumption of the black body and bremsstrahlung core emission mechanisms respectively.

Table 1

| Core emission | SL state | Dipole emission model | Flash duration |
|----------------------|-------------------|------------------------------|-----------------------|
| black body | no (small) dipole | refraction | tens of nsec |
| | | two component | tens of nsec |
| | dominant dipole | refraction | tens of nsec |
| | | two component | tens of psec |
| bremsstrahlung | no (small) dipole | refraction | tens of psec |
| | | two component | tens of psec |
| | dominant dipole | refraction | tens of psec |
| | | two component | tens of psec |